United States Society on Dams

USSD

The Aging of Embankment Dams

May 2010

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Prepared by the USSD Committee on Materials for Embankment Dams

U.S. Society on Dams

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To be the nation's leading organization of professionals dedicated to advancing the role of dams for the benefit of society.

Mission — USSD is dedicated to:

- Advancing the knowledge of dam engineering, construction, planning, operation, performance, rehabilitation, decommissioning, maintenance, security and safety;
- Fostering dam technology for socially, environmentally and financially sustainable water resources systems;
- Providing public awareness of the role of dams in the management of the nation's water resources;
- Enhancing practices to meet current and future challenges on dams; and
- Representing the United States as an active member of the International Commission on Large Dams (ICOLD).

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FOREWORD

The USSD Committee on Materials for Embankment Dams has prepared this White Paper on *The Aging of Embankment Dams*. The White Paper is of interest to owners of dams and those responsible for the safety of existing dams. It points out that there are aging processes, and a project may be developing aging characteristics which need to be examined, studied and remedied to preclude a safety issue. For designers of new dams, it provides a checklist of conditions which could lead to early aging becoming a safety issue and for which designs could be developed to preclude or to mitigate the effects of aging. The White Paper is a summary of the chapter on embankment dams from ICOLD Bulletin No. 93, *Ageing of Dams and Appurtenant Works*, with additional commentary by USSD.

USSD Committee on Materials for Embankment Dams (2009)

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INTRODUCTION

Aging or deterioration of embankment dams and their foundations is of concern to persons involved in their design, construction and operation. These concerns extend throughout the entire life of the dam until safe abandonment or demolition. Design may mitigate effects of aging. Vigilance during construction may correct conditions contributing to aging. Monitoring during operation may identify aging processes which could impact on dam safety. The aging of dams, constructed of earth and rockfill material, as defined herein is due to time-related changes in the properties of the materials of which the structure and its foundation are composed.

The International Commission on Large Dams (ICOLD), Committee on Dam Ageing, studied the various aging phenomena of concrete and embankment dams and appurtenant works (1986 – 1993) and prepared a report on their findings. The report has been published as an ICOLD Bulletin No. 93. (Reference.1) The Committee identified features of deteriorated structures, the processes of deterioration, good design practices, surveillance, detection and rehabilitation. Methods by which the deterioration may be controlled and perhaps prevented were also identified. This White Paper is a summarization of the Bulletin No. 93 chapter on embankment dams, with additional comment. This paper has been prepared by the United States Society on Dams (USSD), Committee on Materials for Embankment Dams.

AGING SCENARIOS

For an understanding of aging, it is necessary to establish the relationship between cause and effect leading to the degradation in structural properties of the dam or foundation. These processes are referred to as scenarios. The causes originate actions on the dam and/or foundation and may affect the material's structural properties. The consequences of deterioration may sometimes only be observed after some years of operation. Deterioration scenarios were identified from collected case histories in several ICOLD publications and were supplemented by additional published case histories. The sources are identified in ICOLD Bulletin No. 93. Table 1 lists the major aging scenarios for earth and rockfill dams and states the number of case histories studied for each scenario. The literature contains many additional case histories of aging, which have been reported on since Bulletin No. 93 was prepared. This is especially evident in the area of geosynthetics because the use of geosynthetics in embankment dams is relatively recent. The Annual USSD Conference Proceedings, the triennial ICOLD Congress Proceedings, the annual IFAI Conference Proceedings, as well as the journals of engineering societies and journals specific to the dam construction industry (*International Journal on Hydropower & Dams*, and *Water Power & Dam Construction*) are sources for further study of the aging of embankment dams.

Table 1 (Reference 1)

Foundation (soil or rock mass) (111 case histories)	-- Deformation (11)* -- Loss of strength, uplift pressure increase and change in state of stress (24) -- Internal erosion (64) -- Foundation degradation (12)
Dam body (embankment materials) (185 case histories)	-- Deformation (31) -- Loss of strength (18) -- Pore pressure increase (20) -- Internal erosion (28) -- Embankment degradation (32) -- Surface erosion (56)
Other (20 case histories)	-- Seepage through concrete faced rockfill dams (7) -- Permeability change (1) -- Loss of bond between concrete structure and embankment (12) -- Aging of geosynthetic materials (0)
(316 case histories)	

* number of case histories in the ICOLD Bulletin

DETECTION AND MEASUREMENT OF AGING

Detection and measurement are the basis for control of the aging scenarios. An up-to-date knowledge of the dam condition is required so that anomalous behavior is detected in sufficient time to allow appropriate intervention to correct the situation and avoid severe consequences. Direct evaluation of aging is possible by monitoring changes in structural properties. Indirect evaluation is by monitoring the effects and consequences of changes and the actions causing them. It is important to establish and maintain a strong data base to assess the impact of aging scenarios on dam safety. Robert B. Jansen stated “Dam owners and engineers have access to a variety of advanced analytical tools for assessing the safety of a dam. When using these tools, it’s important to remember that a mathematical tool is only as good as the data that supports it. Each dam site and its environment is unique, with different characteristics governing performance. This requires sensibly interpreting specific site conditions and their effect on dam safety.” (Reference 2)

SCENARIOS

General

In ICOLD Bulletin No. 93, several case history examples were selected to illustrate each scenario. In order to give the reader a sense of the scenarios, each scenario will be summarized. Included is a description of the scenario, causes, detection, monitoring and remedies. The reader is encouraged to review Bulletin 93 and the more comprehensive ICOLD references listed in the Bulletin.

Foundation

Deformation -- When the foundation consists of very weak rock or deformable soil, the material is usually removed or measures taken to improve the material left in place. If not sufficiently removed, deformations due to consolidation of the soil or weak rock may occur unevenly, resulting in differential settlements, which can induce fissuring of the dam body. In dry climates, dry, low density soils decrease in volume (collapse) when they become wetted, which also can induce fissuring. The fissures may be a source of piping.

To avoid detrimental effects, construct zones of granular self-healing material to mitigate effects of fissures and provide drainage. Foundation settlement may be monitored with instruments installed during construction. Fissuring may be counteracted by intersecting the fissure system with a diaphragm wall.

Loss of strength, increase in uplift pressure and change in state of stress – Loss of material strength, increase in uplift pressure, and a change in the state of stress are phenomena associated with mechanical failure by shear. These phenomena may take place singly or in combination and lead to progressive deterioration of the foundation. Loss of strength generally occurs in clay soils due to saturation and excessive strain. Higher plasticity clays with high dry strength will experience strength loss upon saturation. When clay soils are strained past their peak strength, they experience a significant loss of strength.

Uplift pressure builds up where the steady state seepage is obstructed or where a sudden excess in seepage cannot be accommodated. In rock with erodible or soluble joint infilling under reservoir pressure, water penetrates the joints and progressively builds up the uplift pressure. Water seeping under the dam may move fines which may progressively clog the drain filter or drain openings, resulting in pressure build up at the downstream toe. Water seeping through poorly graded material may move material (internal erosion or piping) leading to subsidence or sinkholes.

Embankments constructed in a narrow valley affected by cross valley arching may experience a decrease in vertical loading on the foundation leading to hydraulic fracturing and eventual piping of foundation material. Cyclic change of stress in the bottom of large seasonal reservoirs induces alternating shear stresses which can lead to a progressive opening of joints. When dams are founded on alluvium, lowering of the downstream water table will increase the effective stress in the soil and may lead to settlement. Design considerations include complete or partial removal of materials prone to loss of strength or the addition of a stability berm. Piezometers may be used to monitor uplift. Observations for excessive seepage or unusual movement of the embankment may detect potential problems.

Internal erosion ─ Erosion processes may only be observed a long time after the first filling of the reservoir, even though they frequently can be related to inadequate design or construction procedures. Internal erosion is the most common aging scenario for the foundation of earth and rockfill dams.

Internal erosion may be envisioned as:

1.) Rock joints are opened by being disturbed during construction and by filling of the reservoir, allowing seepage to begin through the joint network.
2.) Seepage may increase due to aging of the grout curtain by dissolution of the cement; dissolution of gypsum or other minerals; internal instability of the foundation material (abrupt changes in gradation of strata, broadly graded glacial till, dispersive clays, etc.).
3.) Increased seepage flow rates may reach values high enough to cause erosion, which in turn accelerates seepage and erosion.

The most common methods for detection of internal erosion are periodic visual inspection and measurement of seepage. Piezometers are used to detect uplift pressures. Turbidity and chemical analyses are used to detect washed out or dissolved materials.

Remedial measures which have been adopted include grouting, filtered drainage features, relief wells, stability berms, upstream blankets, diaphragm walls and drainage adits.

Foundation degradation ─ Degradation of foundation materials implies that a change occurs in their characteristics or properties resulting in loss of strength or increase in permeability. Materials may degrade due to slaking, dispersion, solutioning, and thermal and chemical processes. Seepage water influences these processes and may take place after first filling or develop slowly over time.

The flow or seepage of water is the primary vehicle in the degradation process resulting in:

1.) Loss of shear strength due to saturation.
2.) Solutioning of minerals.
3.) Removal of erodible, dispersive or soluble material.
4.) Erosion of materials having a high dry bond strength but low saturated bond strength.

An understanding of the physical and chemical conditions within the foundation can greatly enhance a decision making process for selecting remedial treatment of seepage conditions. A well-designed water sampling program, accurate field measurements and chemical data, coupled with analysis of chemical equilibrium and mass balance models can provide an insight to the processes that control the foundation seepage chemistry.

Dam Body

Deformation ─ The long term process of consolidation of the embankment material, after construction completion and during first filling, is the main cause of continuing deformations of the embankment. The consolidation process may be influenced by environmental actions (temperature, precipitation, earthquake, blasting, dam crest traffic) and operational actions (water level fluctuations). Deformation depends upon mineral type, shape, hardness, grain size distribution, and moisture and density of the compacted material.

Consolidation may lead to:

1.) Differential deformation of adjacent sections of embankment, which may cause fissures leading to internal erosion.
2.) Settlement at the contact with a concrete structure initiating cracks, leaks and erosion.
3.) Loss of freeboard.

During design it is important to identify potential long term deformation problems. Harmful effects of deformations can be prevented by appropriate positioning and use of materials, and construction placement and compaction. Monitoring of vertical and horizontal displacements, using surveying methods, settlement monitoring systems or inclinometers, will allow evaluation of deformations.

Loss of strength ─ Loss of strength usually results in instability of slopes and deformation.

Loss of strength of the embankment materials is associated with:

1.) Wetting of improperly compacted embankment soil leading to a loss of strength. Materials compacted dry without the compaction effort to sufficiently reduce the void volume, will experience considerable particle reorientation. If a large mass of embankment is affected, the result would be large settlement. If occasional layers or lenses are affected, the result would be differential settlement possibly leading to cracking, piping and areas of high pore pressure.
2.) Some soils experience a large reduction in cohesion when wetted. Reservoir seepage, abutment groundwater and rainfall wetting the downstream shell may affect downstream shell stability.
3.) Loss of strength may be caused by a change in the state of stress. Embankment heightening may stress the existing material beyond its peak strength and a lower residual strength is reached. Cycles of drying and wetting of high plasticity clays may result in slope instability, particularly shallow downstream slips. As the clay

dries, capillary stresses lead to cracking by tension. When water is again available to the crack, material sloughs off into the crack and there is a loss of strength in the swelling clay at the crack face. A progression of these events would reduce the effective dam width and promote other scenarios.

A well compacted embankment is the primary defense. Periodic inspections and displacement measurements are appropriate for detection of this scenario.

Pore pressure increase ─ Long term pore pressure increase, pressure greater than estimated from normal permeability of the compacted soil, is generally associated with progressive opening of transverse cracks in the core or through the whole fill.

Cracking may be caused by differential foundation settlement, differential embankment compression, embankment arching (hydraulic fracture), contact with concrete structures, or drying out of the upper portion of the core during prolonged dry periods. Pressure increase may also be associated with dissolution of dispersive clays, a defective layer in the core, poor material placement, or low permeability downstream of the core.

Good design and construction practices may preclude excessive pore pressure increase by eliminating foundation overhangs, shaping the abutment and structure contact, use of ductile material in the upper part of the dam, adequate drainage downstream and careful material placement.

Detection of the scenario is primarily by visual observation, supplemented by seepage measurements and pore pressure measurements.

Remedial measures have consisted of grouting, installation of a diaphragm wall, drainage improvement and replacement of damaged areas.

Internal erosion ─ This may go unnoticed for a long time, but generally finds its origin in design and construction inadequacies. It may occur in soils susceptible to cracking, piping or other types of erosion.

Internal erosion may occur within the embankment core or in the downstream shoulder. Quite frequently it occurs at the embankment contact with the foundation. Erosion of embankment material may be through fissured rock or into solution cavities along with erodible rock fissure infilling. Erosion of embankment may be via embankment cracking, internal instability of earthfill (glacial till), dispersive clays, or leaching of soluble minerals. Removed material induces settlements and local failures occur (sinkholes).

Detection of internal erosion has relied on visual inspection, water flow measurements, pore pressure readings, and turbidity measurements. Drilling (using sonic drilling or other drilling method without drilling fluid) and geophysical investigations (temperature measurements and magnetic resonance imaging) have been carried out to determine the extent of the erosion.

Remediation has included grouting the piping path, diaphragm wall, drain system replacement and replacement of affected embankment section.

Embankment degradation ─ Degradation implies that there is a change in characteristics or properties of the materials. This results in a loss of strength or an increase in permeability. Seepage is an important element for these degradation processes, which may be removal of erodible, soluble or dispersed material. Saturation may cause loss of shear strength.

Control of seepage with a well compacted embankment and internal filter and drain features are the best defense. Some rock types, particularly shales, deteriorate when exposed to air and moisture in an unconfined condition. If shales are used in a rockfill, they may deteriorate or weather into a soil, resulting in surface deformation or lowered shear strength of the rockfill allowing slope instability.

Control of seepage is important. Measurements of seepage water volume and water analyses are used to monitor embankment behavior.

Surface erosion ─ Surface erosion, although a very common aging scenario, has not been an important contributor to embankment failures. Surface erosion is readily detected by routine visual inspection and repairs would be undertaken in a timely manner. Erosion on the downstream slope and crest may be due to heavy direct rainfall or surface water runoff, brief crest overtopping, wave spray over a wave wall or wind driven wave spray. Erosion on the upstream slope may be due to wave action on too small riprap or inadequate bedding, breakdown of riprap or freeze – thaw displacement.

Timely repair of upstream and downstream slope erosion is important. Downstream slope improvement includes directing crest runoff into the reservoir and collecting and diverting surface water down and away from the downstream slope.

Regular visual inspections and particularly following unusual weather events are necessary.

Other

Analysis of data on the deterioration of earth and rockfill dams pointed out other aging scenarios concerning the behavior and materials of some specific dam elements.

Seepage through concrete faced rockfill dams ─ This scenario has been only reported for dams constructed of dumped or sluiced rockfill with little or no roller compaction. The dams usually have a system of vertical and horizontal face slab joints, which is no longer in favor. Problems were detected early, however remedial measures were only undertaken when the seepage became too large or limitations on operation were found too restrictive. Excessive settlement of the rockfill led to damage of the joints and even slab buckling. The high permeability of the rockfill led to large seepage, however internal erosion was not a problem. Repairs were made to bring the designs up to present standards.

Detection of this scenario is by visual inspection and measurements of flow and displacement of the slabs and joints.

Permeability change ─ Internal erosion may be considered a scenario of permeability increase. However, the long term effects of seepage may effect a permeability decrease as evidenced by a decrease in total seepage and in the seepage gradient. The permeability decrease may be due to consolidation of the earthfill, which reduces porosity; sealing or deposition of fines in the voids of the earthfill or foundation; or clogging of the filters around drains. Contributing factors may be the chemical composition of the seepage water, the velocity of seepage, or the type of fine particles being carried and deposited or being removed. Movement of fine particles may block seepage paths and increase pore pressure, or permeability may be increased by opening seepage paths.

Monitoring of this scenario is by measurement of seepage flow and chemical content, pore pressure measurements, visual observations of wet areas and geophysical investigations.

Loss of bond between concrete structure and embankment ─ The deterioration of embankments adjacent to concrete structures is associated with differential movements in the bonding zone. Displacements of the bonding zone may be due to settlement of the embankment material due to inadequate compaction or internal erosion. Settlement of the foundation due to inadequate treatment may also be a cause. Settlements may lead to arching in the fill and a reduction of the effective stress. Seepage develops through cracks in the fill or along the concrete structure promoting internal erosion and failure if the filter-drainage system is insufficient.

This scenario is detected by inspection for vertical displacements and seepage.

Aging of geosynthetic materials ─ Geosynthetic materials are being used for water barriers (geomembranes), material separators, filters (geotextiles), drainage features (pipes, erosion control) and stabilization features (geogrids, geotextile wraps).

The common aging agents of geosynthetic materials are ultraviolet light, stress, temperature, moisture extraction, oxidation, chemical and biological. The construction period, including the storing, handling and installation can be the most damaging from the standpoint of the product experiencing an accelerated aging during installation. Select formulations of a product that will be resistant to aging processes and be compatible with the environment into which it is placed. Utilize handling and installation methods which preclude damage which in turn hastens aging.

Monitoring of the aging process may be carried out by retrieving, from time to time, test pieces from a project field test section and carrying out physical and mechanical tests.

The literature on geosynthetics contains reports on aging and monitoring of field installations, (References 3, 4, 5).

Aging of asphalt concrete facing ─ The bituminous material coating and binding together the aggregates in asphalt concrete breaks down from exposure to oxygen and ultraviolet light. Abrasive debris and wave action removes the bituminous coating from aggregates allowing weathering of the aggregates. These aging scenarios if allowed to occur will deteriorate the asphalt concrete water barrier. However, these scenarios need not occur if the original design includes a surface coating of bituminous mastic and if the mastic coating condition is monitored and replaced if it becomes damaged. Mastic coatings have been in place over 25 years without replacement on some dams. Flames used in contact with the asphalt concrete for heating previously placed material cause severe deterioration of the bituminous material. (Reference 6)

Asphalt concrete may also be used for construction of an internal water barrier (core). No examples of aging were found. Only a very poorly designed and constructed asphalt concrete core would be suspect for aging. (Reference 7)

Aging of Soil-Cement ─ Soil-cement slope protection may age from the effects of freeze-thaw action, abrasive debris and wave action. Deterioration of soil-cement protection may be hastened due to insufficient cement in the mix, poor mixing, insufficient compaction or lack of bond between layers. Soil-cement placed in stair step fashion is sufficiently massive that repairs would only be necessary if large segments of protection are lost. Aging damage of soil-cement placed by the plating method requires immediate repairs. See 4.4.3 above for additional comment. (References 8, 9)

DESIGN RECOMMENDATIONS

General

Prevention and mitigation of aging will best be achieved through quality design, construction and operation. A well planned and performed monitoring program is key to early detection of aging scenarios. Providing convenient access to all vital areas of the dam will enhance surveillance and maintenance. Regular maintenance is important.

Foundation

Dams on a foundation of deformable soil should be zoned with granular self-healing material. Complete or partial removal of clays prone to loss of strength or a stability berm may be appropriate if removal is inconvenient.

Control of uplift pressures may be achieved with an appropriate combination of an impervious cut-off and drainage provisions.

Prevention of internal erosion of foundation materials will rely on seepage control, control of uplift pressures and filtering of seepage exits.

Embankment

Excessive or differential deformations may be prevented by appropriate material selection, zoning and compaction.

Cracking of the dam core may be avoided by placing ductile material at locations subject to tensions, shaping abutments to have smooth transitions from area to area and batter appurtenant structures to permit full compaction and bonding of the core, adopt a zoning that does not place materials with large differences in deformation modulus next to each other, use wide excavations and flat slopes to prevent arching and flare the core at abutment interfaces.

Relieve excess pore pressure with internal drainage.

Prevent internal erosion with a self healing transition zone upstream and a filter zone downstream of the core, design to preclude core cracking, avoid internally unstable materials, treat fissured bedrock and treat dispersive soils.

If instrumentation is to be installed within the dam core, it should be designed and installed so that it does not become a risk for future degradation of the dam. There is a risk for gradual erosion of poorly compacted material around vertical riser pipes or tubing used for pressure measurements or internal movement measurements.

Prevent degradation of materials with full compaction, seepage control, use of filters, selection of materials and treatment of dispersive soils.

Mitigate slope protection deterioration with riprap of appropriate durability, size, grading, thickness, slope inclination and proper placement; increase thickness of less quality rock and provide bedding to prevent erosion of underlying embankment.

Where the only rockfill available may experience deformations, which could be unacceptable for a concrete face, consider use of an asphalt concrete face or a central asphalt core.

The use of geosynthetic materials requires careful study of their composition and manufacture, characterization of the environment into which the materials will be installed, and planning of the storage, handling and installation to avoid accelerated aging. Periodic retrieval of coupon samples from a field test section for testing and evaluation is recommended.

The use of asphalt concrete requires careful selection of the bitumen and aggregates, complete mixing, temperature control, and compaction to maintain about 3% voids. Design mixes are tested in a laboratory to assure engineering properties.

Soil-cement requires careful selection of the soil to be mixed with cement and water. Design mixes are tested in a laboratory to assure engineering properties.

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